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*Published in:*  
I E E E Photonics Technology Letters

*Link to article, DOI:*  
[10.1109/68.275450](https://doi.org/10.1109/68.275450)

*Publication date:*  
1994

*Document Version*  
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

*Citation (APA):*  
Jørgensen, B. F., Pedersen, R. J. S., & Jørgensen, C. G. (1994). Self-phase modulation induced transmission penalty reduction in a 5 Gbit/s FM/AM conversion system experiment over 205 km of standard fiber. *I E E E Photonics Technology Letters*, 6(2), 279-281. <https://doi.org/10.1109/68.275450>

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# Self-Phase Modulation Induced Transmission Penalty Reduction in a 5 Gbit/s FM/AM Conversion System Experiment over 205 km of Standard Fiber

Bo Foged Jørgensen, Rune J. S. Pedersen and Carsten Gudmand Joergensen

**Abstract**— The transmission penalty of a standard non-dispersion shifted fiber is experimentally demonstrated to be reduced by Self-Phase Modulation due to the optical Kerr effect. A 2 dB reduction of transmission penalty is achieved in a 5 Gbit/s FM/AM conversion system experiment over 205 km of fiber. The origin of transmission penalty change is discussed for clarification of the important interaction between modulation induced frequency chirp, Self-Phase Modulation and group velocity dispersion in systems with high-power transmitters.

## I. INTRODUCTION

THE GROUP velocity dispersion penalty of an optical communication system depends to some extent on the frequency chirp of the transmitted signal. One way to diminish the dispersion penalty is by introducing a suitable chirp in the transmitted signal in order to obtain less dispersive pulse distortion. Different modulation techniques have been suggested for reduction of the penalty for transmission over standard non-dispersion shifted fibers [1]–[4].

Application of these techniques can not solely be based on linear dispersion conditions in systems that require high-power transmitters. In systems of that kind, fiber non-linearity such as Self-Phase Modulation (SPM) due to the optical Kerr effect has to be taken into consideration. Especially, upgrading the bit rate in an embedded unrepeated system may require a high-power transmitter to overcome system loss. Provided that the transmitter output power is sufficiently high, the combined effect of modulation induced chirp, SPM and group velocity dispersion has significant influence on the system performance.

Amplitude Shift Keying transmission supported by the effect of SPM over 279 km and 204 km of conventional single mode fiber at 2.5 Gbit/s and 5 Gbit/s, respectively, has been reported elsewhere [5]. Here we report observation of transmission penalty dependence of Self-Phase Modulation in a 205 km system experiment system that employs a 5 Gbit/s frequency modulation (FM) to amplitude modulation (AM) conversion transmitter. A 2 dB reduction of transmission penalty with this modulation scheme is demonstrated experimentally by increasing the transmitter output power from +7 dBm to +14 dBm. The cause of transmission penalty change is discussed from a phenomenological point of view where the

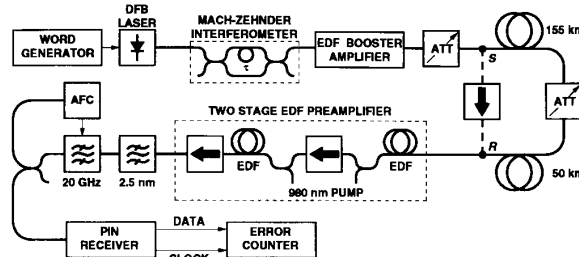


Fig. 1. Experimental set-up.

effect of SPM is accounted for as simple frequency chirping. The discussion clarifies the importance of interaction between modulation induced frequency chirp, SPM and group velocity dispersion in systems with high-power transmitters.

## II. EXPERIMENTAL SET-UP

The experimental set-up is shown schematically in Fig. 1. A three-electrode  $\lambda/4$ -shifted DFB laser with a 10 GHz FM-response bandwidth is used as transmitter [6]. The laser is operated at a wavelength of 1548 nm and the linewidth is 2 MHz. The laser is modulated directly from the word generator with a 5 Gbit/s Pseudo Random Binary Sequence of length  $2^7 - 1$ . The Continuous Phase—Frequency Shift Keying (CP-FSK) signal of the transmitter laser is converted into an AM signal by the Mach-Zehnder interferometer (MZI). The differential delay of the MZI is  $\tau = 42$  ps. An Erbium Doped Fiber (EDF) booster amplifier with a saturated output power of +15 dBm is used in the transmitter. The level of the transmitter output power is adjusted by an optical attenuator.

The receiver is an optically preamplified pin-detector receiver. The two stage EDF preamplifier is pumped at 980 nm. The fiber-to-fiber gain (including input and output connector insertion loss) is 34 dB and the corresponding noise figure is 4 dB. An optical Fabry-Perot filter with a 3 dB bandwidth of 20 GHz ensures that the noise in the receiver is dominated by signal-spontaneous emission beat noise. The filter is locked to the signal by an Automatic Frequency Control (AFC). The periodic frequency response of the Fabry-Perot filter is eliminated by a broadband optical bandpass filter with a bandwidth of 2.5 nm. A fourth-order Bessel filter with 3 dB cut-off frequency of 4 GHz is used as post-detection filter. The

Manuscript received July 8, 1993; revised November 24, 1993.

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IEEE Log Number 9215921.

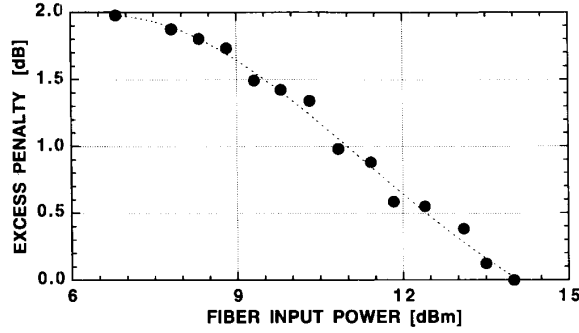


Fig. 2. Excess penalty (@ BER =  $10^{-9}$ ) relative to the transmission penalty at +14 dBm of input after 205 km.

Bit Error Rate (BER) is measured with the error counter which is synchronized by a clock signal recovered by the receiver.

205 km of standard non-dispersion shifted optical fiber is inserted in between the transmitter and the receiver. The fiber length is chosen as a compromise between the available dynamic range of input power and the amount of dispersion penalty. The average dispersion of the fiber is 17 ps/nm/km and the loss is 0.21 dB/km. The transmission fiber is separated in two sections of 155 km and 50 km, respectively. In between the two sections is a second optical attenuator applied in order to vary the level of the received power which is referred to the input connector of the optical preamplifier.

### III. EXPERIMENTAL RESULTS

Baseline measurement of the bit error rate is performed with an optical isolator inserted in between point 'S' and 'R' as indicated in Fig. 1. The FM index,  $\beta$ , is adjusted to find optimum received sensitivity. For  $\beta = 2.4$ , the extinction ratio at the output of the MZI is measured to approximately 13 dB and the receiver sensitivity is -40.3 dBm @ BER =  $10^{-9}$ .

Transmission experiments are performed with the isolator replaced by the 205 km of fiber. BER measurements are performed at different levels of fiber input power up to +14 dBm. The receiver sensitivity at +14 dBm of input power is optimized by adjustment of the FM index to  $\beta = 1.6$ . The change of  $\beta$  reduces the extinction ratio to approximately 10 dB. For this case, the receiver sensitivity is -38.7 dBm @ BER =  $10^{-9}$  corresponding to a transmission penalty of 1.6 dB with reference to the baseline sensitivity. The excess penalty relative to the transmission penalty at +14 dBm (@ BER =  $10^{-9}$ ) is shown as a function of fiber input power in Fig. 2. The slope decreases towards low input power which indicates that the linear dispersion regime is encountered for decreasing input power. Reduction of the fiber input power to +7 dBm results in an additional penalty of 2.0 dB. The input power in the experiment can not be reduced below +7 dBm due to fiber losses. The slope also decreases towards high input power as a result of the existence of a minimum transmission penalty limit (c.f. the following discussion). However, the saturation output power of the booster amplifier available for this experiment was too low to verify the existence of the minimum transmission penalty limit.

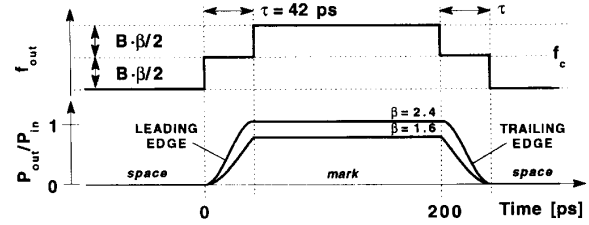


Fig. 3. Time dependent output power and output frequency of the FM/AM converted signal.

### IV. DISCUSSION

Qualitatively, the behaviour of the experiments can be understood from simple considerations on the combined effect of Self-Phase Modulation and group velocity dispersion. For this purpose we assume that the effect of SPM initially is separated from the effect of dispersion. Therefore, SPM results in simple modification of frequency chirp [7]. The effect of dispersion is next conceived as energy carried at individual propagation velocities corresponding to distinct frequencies defined by the chirp [8]. Ideally, the output power  $P_{out}(t)$  and the time dependent output frequency  $f_{out}(t)$  of the MZI can be shown to be expressed as

$$P_{out}(t) = \frac{P_{in}}{2} \left[ 1 + \cos \left( 2\pi \int_{t-\tau}^t f_{in}(t') dt' \right) \right] \quad (1)$$

$$f_{out}(t) = \frac{1}{2} [f_{in}(t) + f_{in}(t - \tau)] \quad (2)$$

where  $P_{in}$  is the input power and  $f_{in}(t)$  is the time dependent input frequency that represents the transmitted bit pattern. The two discrete levels of  $f_{in}(t)$  are  $f_c \pm B \cdot \beta/2$  ('+' for one logical value and '-' for the logical complement), where  $B$  is the bit rate and  $f_c$  is the carrier frequency. It is seen from (1) that the output power is constant for a constant input frequency whereas the power changes in a sinusoidal manner within a time period of  $\tau$  following the appearance of a logical shift. We refer to the constant part of maximum (minimum) power as a 'mark' ('space') while the transition between a space (mark) and a mark (space) is referred to as the leading (trailing) edge.  $P_{out}$  and  $f_{out}$  are shown in Fig. 3 for a mark arbitrarily represented by the maximum frequency. For this case, the edges are red-shifted with respect to the frequency of a mark. The opposite choice of frequencies causes the edges to be blue-shifted with respect to the frequency of a mark but it does not affect the system performance. The extinction ratio of the output signal is for simplicity assumed to be optimized by adjustment of the carrier frequency so that the power of a space equal zero.

The dispersion will cause the energy of the edges to propagate at a lower velocity than the energy of a mark. This implies, that energy of a leading edge flows into the mark while energy of a trailing edge flows into the space. The amount of energy flow increases with the transmission distance which results in an increased dispersion penalty due to distortion and inter symbol interference. SPM induced frequency chirp is red-shifted (blue-shifted) on a leading (trailing) edge of a pulse. The instantaneous magnitude of the SPM induced

angular frequency chirp is  $-z_{\text{eff}}\gamma dP_f/dt$  [7], where  $z_{\text{eff}} = 21$  km is the effective non-linear interaction length,  $\gamma = 2.7$  (W km)<sup>-1</sup> is the non-linearity coefficient and  $P_f$  is the fiber input power. Quantitatively, the peak magnitude of the SPM induced frequency chirp can be shown to vary from 1.4 GHz to 6.8 GHz at  $\beta = 2.4$  and from 1.2 to 6.2 GHz at  $\beta = 1.6$  for the average input power varying between +7 dBm and +14 dBm. The corresponding magnitude of the modulation induced frequency chirp is 6 GHz at  $\beta = 2.4$  and 4 GHz at  $\beta = 1.6$ . Consequently, the SPM induced chirp significantly intensifies the frequency chirp at the leading edge but counteracts the frequency chirp at the trailing edge. Thus, for a given length of transmission fiber and a given modulation index, an increasing input power up to some point is expected to reduce the transmission penalty because the amount of energy flow from a trailing edge into the adjacent *space* is reduced. However, the reduction of transmission penalty is counteracted by the accompanying increased amount of energy flow from a leading edge into the adjacent *mark* due to the red-shifted modulation induced frequency chirp. The modulation induced chirp (c.f. Fig. 3) and thus the transmission penalty can for a given input power be reduced by reduction of  $\beta$ . If the input power is unceasingly increased, SPM induced frequency chirp progressively dominates which eventually will cause the transmission penalty to increase due to a growing amount of energy flow from a leading (trailing) edge into subsequent (precedent) symbols.

The modulation induced chirp of the FM/AM converted system is unique because the leading edge and the trailing edge are equally frequency shifted with respect to the frequency of a *mark*. As a result, modulation induced chirp and SPM induced chirp can not be combined constructively to eliminate the transmission penalty. Provided that the interaction between modulation induced frequency chirp, SPM and dispersion is taken properly into account, high-power transmitters with opposite sign of the modulation induced frequency chirp of a leading edge and a trailing edge appear more attractive since constructive balance between modulation induced chirp and SPM can be obtained.

## V. CONCLUSION

A 2 dB reduction of transmission penalty of 205 km of standard non-dispersion shifted fiber has been achieved in a 5 Gbit/s optical communication system experiment. This reduction has been obtained by non-linear Self-Phase Modulation induced by increasing the input power from +7 dBm to +14 dBm. The origin of transmission penalty change has been discussed. The discussion clarifies the importance of interaction between modulation induced frequency chirp, Self-Phase Modulation and group velocity dispersion in systems with high-power transmitters.

## ACKNOWLEDGMENT

We thank Fujitsu Laboratories Ltd. for supplying the three-electrode laser. We also thank Lycom A/S for supplying the transmission fiber and NKT Elektronik A/S for supplying the booster amplifier and the AFC for the Fabry-Perot filter.

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